Systematic Performance Monitoring and Examination of ZigBee Networks

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***Abstract*—This paper introduces a novel approach for a system-wide performance evaluation of Zigbee networks, in the context of large-scale lighting applications. It allows a comprehensive assessment of Zigbee networks through quantitative measurement of three key performance indicators: Reliability, Robustness, and Responsiveness. It proposes a systematic framework that injects different traffic scenarios into the network to get performance scores for each node in the network for every scenario. These scores are then passed through weighted scoring algorithms to obtain a network-level score for each performance indicator. Weighting factors are computed through the Analytic Hierarchy Process (AHP) that prioritizes multiple criteria based on merit. The framework has been deployed and tested in real-life lighting systems, considering two luminaire network topologies: open-space and corridor layouts. The results show the use of the framework for overall acceptance testing as well as identifying low-performing nodes. Thus, this paper presents a distinctive methodology and a testbed to qualitatively monitor the performance of any Zigbee network deployed for lighting solutions based on user needs.**

***Index Terms*—Zigbee, performance indicators, weighted scoring algorithm, Analytical Hierarchical Process (AHP), scenario score, network metrics**

I. Introduction

Zigbee [1] is one of the most widely used wireless communication protocols in contemporary smart lighting systems. In such systems, luminaires are typically equipped with Zigbee nodes that have multiple integrated functions such as motion, light and temperature sensors. Among others, the sensing functionality brings energy savings through occupancy-based and daylight-aware lighting control. As depicted in Figure 1, hundreds of such Zigbee-enabled luminaires collectively form a wireless mesh network. The network allows to relay sensory and control data between luminaires and a central control hub, also known as network *gateway*. The gateway further publishes the data to a backend server for data-driven Internet-of-Things (IoT) services, which are commonly available via web and mobile applications.

A. Challenges

One of the challenges of indoor Zigbee networks such as smart lighting systems is that their performance could be affected by environmental factors. When large-scale Zigbee networks are newly installed at customer sites such as office buildings, factories and warehouses, devices could malfunction or parts of the network may under-perform. This may result in multiple packet re-transmissions, causing overall network performance degradation.

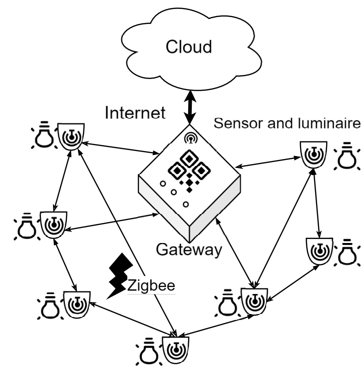

Fig. 1: Zigbee-based Smart Lighting System

Zigbee operates in the 2.4GHz ISM frequency band, where other technologies such as Wi-Fi and Bluetooth also coexist. Radio Frequency (RF) interference from such and other wireless devices could hinder packet transmission and reception. Packet loss can also occur due to the presence of path loss elements and signal attenuation due to various building materials. As a result, it is crucial to execute an acceptance test to assess the overall performance of a newly set up network. Once the system is operational, it is also imperative to reexamine the network after major changes such as Zigbee stack firmware updates, network expansions as well as reconfiguration of network parameters such as transmission power, data rates and payload sizes.

B. Contributions

This paper proposes a new comprehensive methodology to analyse the overall performance of a given Zigbee network. Moreover, the methodology allows to identify poorly performing nodes for further troubleshooting. To that end, it makes the following novel contributions.

1) It introduces three quantitative *Performance Indicators*, namely *Reliability, Robustness, and Responsiveness*, to get insight into the overall health of a Zigbee network. This is achieved by combining low-level network metrics such as packet delivery and end-to-end latency with the injection of dynamic network traffic scenarios.
2) It presents a weighted scoring algorithm for each performance indicator, where weighting factors can be flexibly adjusted based on the prioritization of different criteria.

3) It devises a framework to deploy the evaluation methodology into existing network installations to allow performance monitoring under different system use-cases.

C. Scope

This work primarily targets indoor Zigbee networks, where nodes are not mobile, not battery-powered and can communicate through a mesh network topology. Furthermore, a Zigbee *coordinator* is assumed to be present, towards which most packet traffic is concentrated as it collects metrics and sensory data from all other nodes in the network.

The paper proposes the new comprehensive methodology of performance evaluation of Zigbee networks by first giving an overview of existing works in section II and the different metrics considered by them. Section III lists out the basics of Zigbee and the importance of Analytic Hierarchy Process (AHP) for this paper. Section IV discusses the proposed framework, the performance indicators chosen and the algorithm developed to quantify them. Section V explains the setup over which the framework is evaluated and the results obtained. Finally, section VI concludes the results and describes possible areas of future work.

II. Related Work

Various works have been previously done on performance analysis of Zigbee networks. [1] explores the efficiency of Zigbee in wireless electricity meters. It has conducted experiments under different scenarios to observe values such as Round Trip Time (RTT), packet loss and received power. [2] presents an experimental evaluation of Zigbee networks where network parameters such as throughput, RTT, Received Signal Strength Indicator (RSSI), and Routing Recovery Time have been analysed. The work presented in [3] analyzes the performance of ZigBee networks by considering variable network sizes. The metrics used for analysis included Packet Delivery Ratio (PDR), end-to-end delay and energy consumption. The comparative study in [4] attempts to study the advantages of LoRa and Zigbee for IoT applications by studying the PDR and RTT of the respective networks in specific experimental setups. [5] attempts to bridge the gap between technical specifications and real-world field measurements of ZigBee networks. Their paper offers guidance for developing new ZigBee networks by providing expected raw performance data. Silicon Labs report [7] on ZigBee network performance aims to provide designers with an understanding of different use cases and the expected performance within those scenarios. The report utilizes varying network sizes and different message types (unicast and broadcast) as testing benchmarks to gain insight into the reliability and scalability of ZigBee networks. It analyzes latency with different payload sizes and packet intervals and tests the network's range in terms of average round trip and expected packet loss.

In the aforementioned works, two key network metrics stand out in assessing network performance: latency (RTT) and packet loss (PDR). Nevertheless, these works do not aim to provide a comprehensive approach where the performance of a given Zigbee network can be quantified and compared over time. The approach presented in our paper combines metrics from individual nodes through a scoring algorithm to compute a network-level score. As such, the performance of individual nodes is expressed through a statistical summary of node-level metrics (such as PDR and latency), while the network-level assessment is presented through percentage scores under different Performance Indicator categories.

III. Preliminaries

This section recaps the basics of Zigbee and the Analytic Hierarchical Process (AHP). Section III-A and III-B summarize key Zigbee terminologies. Section III-C gives a brief introduction to AHP, which is the technique applied in this paper to compute weighting factors in scoring algorithms.

A. Zigbee Mesh Network

Zigbee is a wireless communication protocol that is based on IEEE 802.15.4. Its design focuses on low-bandwidth and low-power systems, such as Wireless Sensor Networks (WSNs). Hundreds (even thousands) of Zigbee devices collectively form a mesh network. Zigbee devices (a.k.a *nodes*), that participate in data *packet* routing are called *Routers*. A Zigbee network may also have one special device, called the *Coordinator*, that is responsible for network creation and maintenance. In Zigbee-based IoT systems, the Coordinator is typically embedded in the *Gateway*, which is the interface device between a Zigbee network and the cloud backend. In such systems, the Gateway serves as a data-concentrator, where the majority of Zigbee packets are destined.

B. Network metrics

Key network metrics that are often used for performance analysis, fault diagnosis and optimisation of Zigbee networks are the following.

- **Packet Delivery Ratio (PDR)** of a node n, also known as its packet loss, is defined as the ratio between the number of data packets successfully delivered to it (P_n^R) and the number of packets transmitted to it from source (P_n^T).

$$P_n = \frac{P_n^R}{P_n^T} \tag{1}$$

  Network throughput is also an essential metric, however, the proposed framework, tailored specifically for lighting applications, does not prioritize it as a critical factor.
- **Packet latency** ($t_{s \to d}$) is the time taken by a data packet to traverse from a source (s) to a destination node (d), possibly hopping through multiple intermediate nodes.
- **Packet Round Trip Time (RTT)** for a packet m refers to the sum of the packet latency of a transmitted packet ($t_{s \to d}$) and its corresponding response packet ($t_{d \to s}$).

$$L^m = t_{s \to d} + t_{d \to s} \tag{2}$$

C. Analytic Hierarchy Process (AHP)

AHP [8] is a decision-making tool that helps select features by breaking down complex decision problems into smaller, more manageable parts. In the context of a Zigbee network, numerous network metrics impact its performance. However, its health is not affected equally by every metric, across all deployment scenarios.

Thus, there is a need for an algorithm capable of assessing diverse performance aspects of a network and prioritizing or weighting the network metrics and scenarios according to

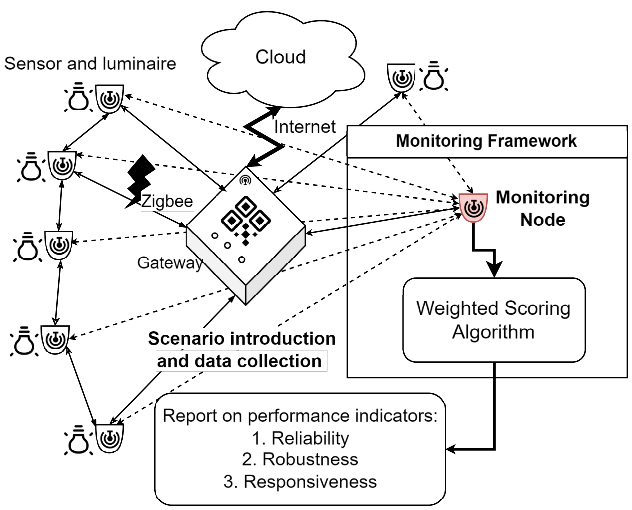

Fig. 2: Deployment of the proposed monitoring framework

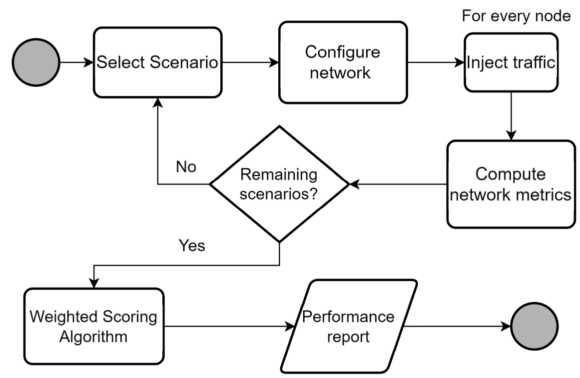

Fig. 3: Performance analysis execution flow

system requirements and user preferences.

AHP provides a flexible method to address this need. It involves the establishment of a hierarchical structure that encompasses criteria and sub-criteria of a task, followed by pairwise comparisons to ascertain their relative significance. Using a predefined scale, users assign values ranging from 1 to 9 to each pair of features/criteria, that reflect their relative importance within the hierarchy. This process generates a square matrix containing the relative importance of the features, which is further analyzed to derive a principal eigenvector. Normalizing this result yields a vector of weights or priorities of the features, delineating the impact each has on the task (in this paper, the performance of the Zigbee network) [9].

IV. Performance Evaluation framework

This section discusses the performance monitoring framework proposed in this paper. Figure 2 depicts a high-level deployment diagram of the framework and Figure 3 highlights the execution steps of the analysis framework. A key component of the framework is a special Zigbee device, called *monitoring node*, that joins an existing Zigbee network. The main role of the monitoring node is to configure the network and inject several traffic patterns, which we refer to as *Dynamic Scenarios* (cf. Section IV-B). The goal is to collect network metrics from every node, under each dynamic scenario. The collected network metrics from all nodes become then input to a *weighted scoring algorithm* (cf. Section IV-C) that performs a quantitative performance assessment. The assessment is reported under different categories, which we refer to as *Performance Indicators* (cf. Section IV-A).

The physical location of the monitoring node in the network can affect its performance results. Unreachability of the monitoring node by other devices can negatively affect the results of the performance indicators. While the idea is to integrate the monitoring node into the coordinator, the current implementation treats it as a separate entity.

A. Performance Indicators

To quantitatively evaluate the performance of a Zigbee network, the framework introduces three performance indicators.

1) **Reliability** of a network is the successful transmission and reception of packets. As such, a network with a low packet loss rate is considered reliable.
2) **Robustness** indicates the consistency of the network's performance irrespective of disruptive changes. For instance, a network that can recover from link failures and find new routes is considered robust.
3) **Responsiveness** is the rate at which the network adapts to changes. This performance indicator, for instance, captures how soon nodes become reachable after a major network-level power failure.

B. Dynamic scenarios

We define a *dynamic scenario* as a specific combination of network parameters such as configuration settings and traffic patterns. Some key parameter types considered in our analysis framework are the following.

- *packet size*
- *transmission (Tx) power*
- *traffic type*: unicast, multicast, broadcast
- *packet send rate*: number of packets sent per second
- *network layout* (i.e. network size and topology)

Our framework assumes a discrete set of values are selected for each parameter type. For instance, configurable packet size and Tx power settings can be respectively given as sets $\{38, 80, \cdots, 124\}$ bytes and $\{-20, -4, ..., 10\}$ dbm. Likewise, network layout can be given as percentages $\{100\%, 90\%, \cdots, 75\%, \cdots\}$ that denote the active network size after random link and power failure modes are introduced in the network.

Given multiple sets of network parameters $A, B, \cdots, \Gamma$, where $A = \{\alpha_1, \alpha_2, \cdots\}, B = \{\beta_1, \beta_2, \cdots\}, \cdots$, the set of all possible dynamic scenarios is given as the cartesian product of these sets, as shown in Eq. 3.

$$\begin{aligned} S &= A \times B \times \cdots \times \Gamma \\ &= \{(\alpha, \beta, \cdots, \gamma) | \alpha \in A, \beta \in B, \cdots, \gamma \in \Gamma\} \end{aligned} \tag{3}$$

The total number of dynamic scenarios $|S|$ is then obtained by multiplying the number of elements of each parameter set: $|S| = |A| \cdot |B| \cdots |\Gamma|$, where $|A|$ denotes cardinality of set A.

C. Weighted Scoring Algorithm

Separate weighted scoring algorithms are developed for each performance indicator. This section presents, the scoring

algorithms for reliability and robustness, while responsiveness is omitted due to space constraints..
The input to the scoring algorithms is the statistical summary of node-level PDRs, shown in Eq. 4 where P_n (see Eq. 1) refers to the PDR of node n and N denotes the network size.

$$P_{\{max,min,avg,std,ji\}} = \{max, min, avg, std, ji\}_{n=1}^{N} P_n \quad (4)$$

In Eq. 4, max, min, avg and std refer to maximum, minimum, average and standard deviation values across the PDRs of individual nodes. ji refers to *Jain's Index* [10], which is calculated as shown in Eq. 5. It is a measure of fairness that indicates the equitable performance of nodes.

$$P_{ji} = \frac{[\sum_{n=1}^{N} P_n]^2}{N \sum_{n=1}^{N} {P_n}^2} \quad (5)$$

1) Reliability

The first step of the algorithm, depicted in Figure 4, is calculating a *Scenario Score (SS)* using Eq. 6, for every dynamic scenario. This score serves as a quantitative indicator of network reliability for a scenario. Higher values of $P_{max,min,avg}$ are desirable as they correspond to low packet loss. A high value of P_{std} shows high variability in PDR across the network, which is undesirable. The impact of P_{ji} depends on P_{avg}. In Eq. 6, $sign = -1$ if $P_{avg} \leq 0.5$ and $P_{ji} \geq 0.8$. If the network experiences low P_{avg} with a high P_{ji}, it indicates that many nodes have high packet loss. This negatively impacts the scenario score. In any other case $sign = 1$.

$$\begin{aligned} SS = & W_{avg} \cdot P_{avg} + W_{min} \cdot P_{min} + W_{max} \cdot P_{max} \\ & - W_{std} \cdot P_{std} + (sign)(W_{ji} \cdot P_{ji}) \end{aligned} \quad (6)$$

$W_{max,min,avg,std,ji}$ in Eq. 6 refer to weighting factors that are calculated using AHP, which builds a weighting matrix (Eq. 7) whose elements represent the relative importance of two PDR statistical summaries. Each element w_i is assigned values from the set $\{1, 3, 5, 7, 9\}$, indicating $\{$*equal, moderate, strong, very strong, extreme*$\}$ comparisons. The normalized eigenvector of matrix W_M of Eq. 7 yields weighting factors $W_{max,min,avg,std,ji}$ in the range $[0, 1]$.

$$W_M = \begin{array}{c} \\ \left(\begin{array}{ccccc} P_{max} & P_{min} & P_{avg} & P_{std} & P_{ji} \\ 1 & w_1 & w_2 & w_3 & w_4 \\ \frac{1}{w_1} & 1 & w_5 & w_6 & w_7 \\ \frac{1}{w_2} & \frac{1}{w_5} & 1 & w_8 & w_9 \\ \frac{1}{w_3} & \frac{1}{w_6} & \frac{1}{w_8} & 1 & w_{10} \\ \frac{1}{w_4} & \frac{1}{w_7} & \frac{1}{w_9} & \frac{1}{w_{10}} & 1 \end{array} \right) \end{array} \begin{array}{c} \\ P_{max} \\ P_{min} \\ P_{avg} \\ P_{std} \\ P_{ji} \end{array} \quad (7)$$

After a scenario score SS_i is obtained for each scenario i with Eq. 6, its scenario weight SW_i is computed using AHP, based on its relative importance. E.g., scenarios with default network settings could carry higher weights than other corner-case scenarios. Following this, theoretically possible max and min scenario scores (SS_{max} and SS_{min}) are calculated. SS_{max} occurs when there is 0% packet loss and SS_{min} occurs when there is 100% packet loss. These terms are combined to

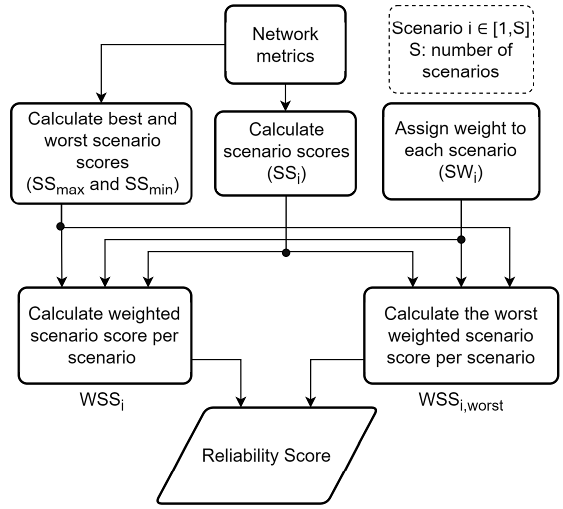

Fig. 4: Weighted scoring algorithm for reliability

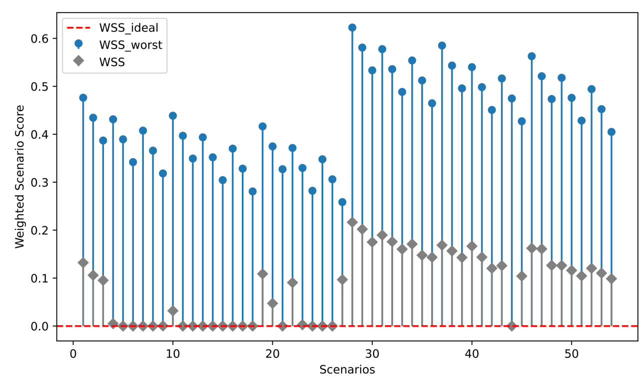

Fig. 5: Weighted Scenario Scores for reliability

compute Weighted Scenario Score (WSS_i) and $WSS_{i,worst}$ for each scenario i, as given by Eq. 8.

$$\begin{aligned} WSS_i &= (SS_{max} - SS_i)^2 \times SW_i \\ WSS_{i,worst} &= (SS_{max} - SS_{min})^2 \times SW_i \end{aligned} \quad (8)$$

Figure 5 illustrates WSS, WSS_{worst} and WSS_{ideal}. When WSS = $WSS_{ideal} = (SS_{max} - SS_{max})^2 \times SW_i = 0$, there is no packet loss (maximum reliability). Scenarios with WSS closer to WSS_{worst} indicate high packet loss (low reliability). The reliability performance indicator is finally obtained by Eq. 9, where S denotes the set of all scenarios (cf. Eq. 3).

$$Reliability = \left(1 - \frac{\sum_{i=1}^{|S|} WSS_i)}{\sum_{i=1}^{|S|} WSS_{i,worst}}\right) \times 100\% \quad (9)$$

2) Robustness

The robustness score indicates the network's ability to maintain acceptable performance despite disruptive changes. Link failures (e.g. due to interference, power issues and congestion) could make parts of the network unreachable. When such issues occur, the network size and topology changes, resulting in a new *network layout*. Furthermore, this may also lead to higher packet retries that increases latency. Thus, our robustness algorithm considers network layout changes and packet latency, in addition to PDR. During performance analysis, network layout changes can be simulated by making nodes unavailable in some predefined pattern. The scoring algorithm, shown in Alg. 1, first computes scenario scores for each network layout $k \in K$, where K is the set of analysed network layouts. PDR-based scenario score, SS^P is

Algorithm 1 Weighted scoring algorithm for robustness

Require: K is a set of network layouts
Require: S is a set of dynamic scenarios
1: **for** $k \in [1, 2, \cdots, |K|]$ **do**
2:   **for** $i \in [1, 2, \cdots, |S|]$ **do**
3:     SS_i^P ▷ PDR-based Scenario Score, Eq. 6
4:     SS_i^L ▷ Latency-based Scenario Score, Eq. 10
5:     $\overline{SS_i^P}$ and $\overline{SS_i^L}$ ▷ Normalized scenario scores
6:     $W^P, W^L \in [0, 1]$ ▷ Weights for PDR and Latency
7:     Compute scenario score SS_i where
8:     $SS_i = (W^P \cdot \overline{SS_i^P} + W^L \cdot \overline{SS_i^L})$
9:     $\overline{SS_i}$ ▷ Normalized scenario score
10:     $NRS_k = \sum_{i=1}^{|S|} \overline{SS_i}$
11:   **end for**
12: **end for**
13: $NRS_{avg,std} = avg, std(NRS_k$ where $k \in [1, |K|])$
14: $NRS_{cv} = \frac{NRS_{std}}{NRS_{avg}}$
15: $Robustness = (1 - NRS_{cv}) \times 100\%$

calculated using the same Eq. 6, used in reliability scoring algorithm. Latency-based scenario score SS^L is the average latency experienced by every node n in the network of size N. L_n^m (cf. Eq. 2) denotes RTT latency of packet $m \in [1, M]$ where M is the total number packets sent per scenario.

$$SS^L = \frac{\sum_{n=1}^{N} \sum_{m=1}^{M} L_n^m}{N \cdot M} \tag{10}$$

Scenario score SS is then a weighted function of PDR-based and latency-based scenario scores, given by line 8, in Alg. 1. This requires normalizing the computed scenario scores within the same range of $[0, 1]$, as indicated in lines 5 and 9. The normalised scenario scores are then combined to compute, what we call *Network Resilience Score* (NRS_k) of network layout k, indicated at line 10. After computing NRS_k, the next step is to assess performance variations across the different network layouts. To that end, we use the statistical unit *coefficient of variation (CV)*, which measures consistency within a data sample set. CV is computed as a ratio of standard deviation to the average of a given data set. This is indicated at lines 13 and 14 for the computation of NRS_{cv}. Finally, the robustness scenario score is given by Eq. 11.

$$Robustness = (1 - NRS_{cv}) \times 100\% \tag{11}$$

V. Evaluation and Results

The framework is implemented and tested in existing networks of Zigbee nodes of Silabs EFR32MG12. This section presents a comparative analysis of results from two separate test runs, executed in *open-space* and *corridor* layouts. Figure 6 represents an open-space layout, which is a typical lighting network deployment in open-offices. Figure 7, the corridor layout, showcases luminaires distributed across two rooms/halls, with the gateway situated in Room 1. The corridor layout is selected to demonstrate the importance the robustness score. If a corridor node fails, it could prevent nodes in Room 2 from connecting to the gateway, potentially leading to significant performance degradation. This would not be the case in the open-space layout.

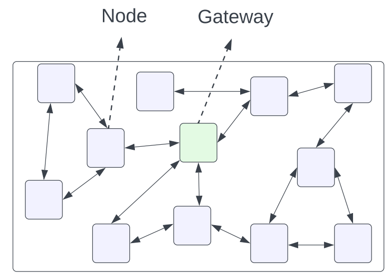

Fig. 6: Open space layout

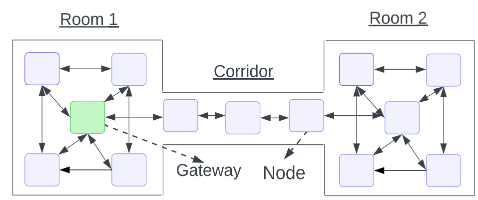

Fig. 7: Corridor layout

A. Setup

The tested network consists of one gateway, one monitoring node, and $N = 33$ sensor nodes in an indoor setting. To assess performance, dynamic scenarios S are injected into the network, varying traffic types (broadcast and unicast packets), adjusting packet send rates {1, 2, and 10} packets/second, payload sizes {37, 98, and 124} bytes and Tx powers {-20, 4, and 10} dBm. Network layout is varied with number of active nodes at {100, 75, 50, 25}% of network size by switching off the radio of *randomly* selected nodes. This results in $|S| = 2 \times 3 \times 3 \times 3 \times 4 = 216$ scenarios with $M = 50$ packets transmitted by the monitoring node for each scenario.

B. Results

This subsection provides the results obtained from the implemented framework.

1) Reliability

Figure 8 and 9 respectively show that the open-space layout is **95.21%** and corridor layout is **89.26%** reliable. In the open-space layout, scenarios 46 to 54 (broadcast packets transmitted at -20dBm) exhibit reliability issues. Similarly, the corridor layout encounters these problems in scenarios 19 to 27 (unicast packets transmitted at -20dBm) and 46 to 54. This observation underscores that nodes within the open-space layout can establish alternative communication paths despite low transmission power, whereas such capability is restricted for nodes in the corridor layout. Thus, the failure of a single corridor node significantly impacts the performance of nodes distant from the data concentrator.

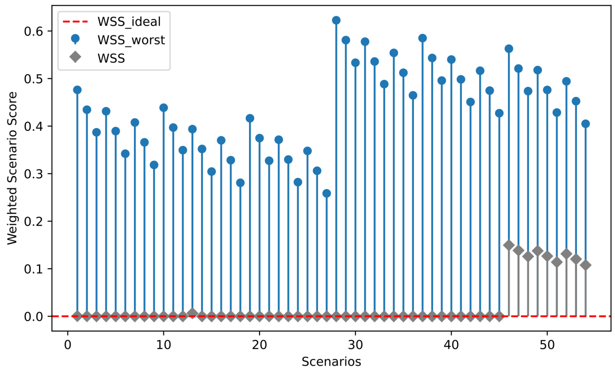

Fig. 8: Reliability Scores for open-space layout

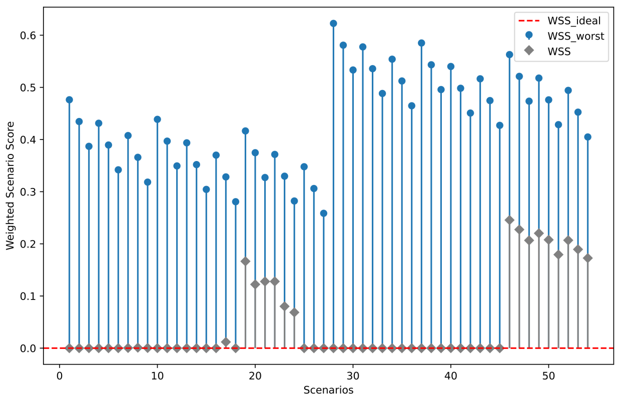

Fig. 9: Reliability Scores for corridor layout

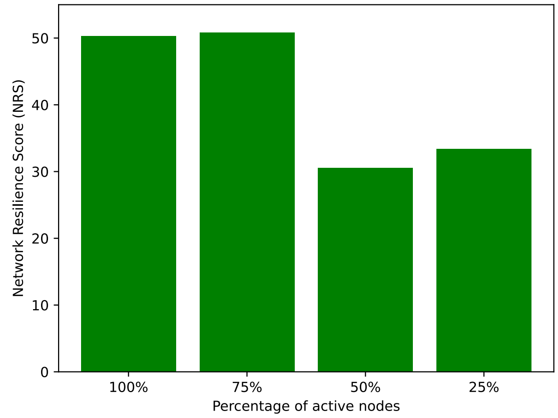

Fig. 10: Robustness Scores for open space layout

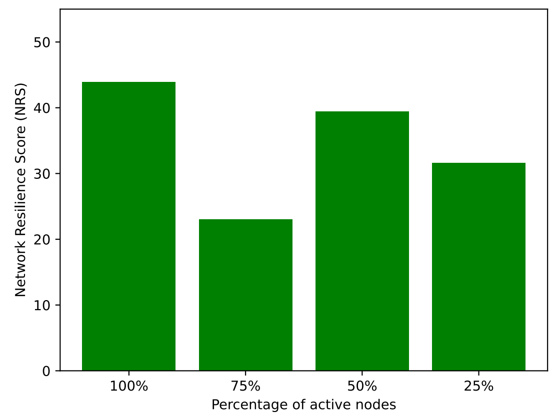

Fig. 11: Robustness Scores for corridor layout

2) *Robustness*

The results show that open-space layout is **77.37%** and the corridor layout is **76.92%** robust. Figure 10 and 11 show the Network Resilience Scores (NRS) obtained across the network layouts. The x-axis represents the percentage of active nodes in each layout.

Initially, the open-space layout exhibits a high NRS, particularly for 100% and 75% active nodes. However, this consistency diminishes significantly with a decrease in active nodes due to a reduction in available routes caused by node failures. The corridor layout starts with a low NRS and shows a further decline when only 75% of the nodes are active. This is because a subset of active nodes, distant from the monitoring node, become unreachable, as nodes on the corridor fail. A subsequent increase in NRS is observed as the network size decreases and the network consists of close-by nodes.

VI. Conclusion and Future Works

This paper presents a systematic methodology to analyse the performance of a given Zigbee network, through quantitative performance indicators such as reliability and robustness. The approach can be used as an acceptance test for new installations and to monitor existing networks after major changes. In addition, it allows identification of poorly performing nodes for further troubleshooting. This is possible because the framework evaluates every node's network metrics (PDR and packet latency) as input for high-level performance scores. The scoring algorithm accepts weighting factors to accommodate varying stakeholder requirements. Weighting factors are calculated through Analytic Hierarchy Process (AHP), where relative importance can be assigned to different parameters. Furthermore, the scope of the performance analysis can be flexibly adjusted through the number and types of dynamic scenarios considered. As an extension, its applicability can be broadened to other wireless protocols such as Bluetooth, LoRa and more, where the networks face similar performance issues.

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